REVIEW

A comprehensive overview of carbon dioxide, including emission sources, capture technologies, and the conversion into value-added products

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Abstract

Carbon dioxide is both the planet's enemy and friend since it maintains the balance of the planet as this gas retains some of the radiant energy that the planet receives. Thus, it keeps the Earth's heat, without which the Earth would be unbearably cold. However, the increase in the quantity of CO_2 in the Earth's atmosphere contributes to the exacerbation of global warming. CO_2 is mainly produced from the processes of combustion of fuel and petroleum, as well as from the breathing process of living organisms. This study aims to provide a comprehensive view of carbon dioxide, including the main sources of emissions that resulted in negative effects, as well as the various ways to control these emissions by conducting a separation process during fuel combustion in power plants and preventing the release of large quantities into the atmosphere. Finally, an objective viewpoint on how to benefit from separated carbon dioxide and turn it into highly valuable products is presented. Given that this is a global problem that affects our planet, this review links other literature that deals with each part separately, and thus it presents a clear and comprehensive vision that enables the reader to be aware of carbon dioxide gas from all perspectives, concluding with future studies that are required to prevent an increase in negative effects in order to preserve the quality of life in our planet.

Graphical abstract
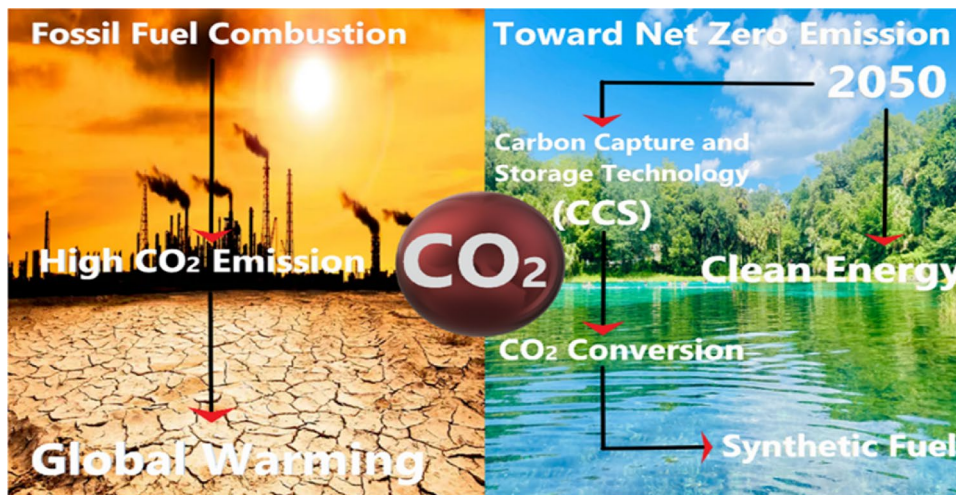
Extended author information available on the last page of the article

Introduction

Fossil fuel combustion by-products such as toxic air pollutants like polycyclic aromatic hydrocarbons, nitrogen dioxide, atmospheric ammonia, and the major climate-altering gas carbon dioxide represent a serious risk to health (Perera et al. 2019; Perera 2018; Zhang et al. 2020) and result in global warming (Inumaru et al. 2021; Janke et al. 2014b). By the end of the century, continuing higher emissions of greenhouse gases could increase greenhouse gas concentrations in the atmosphere to approximately four times pre-industrial levels. This would be expected to bring a 3.7 °C rise in global mean surface temperatures (with a likely range of 2.6 °C to 4.8 °C) by the 2090s compared to 1986–2005 temperatures, in addition to the warming of 0.6 °C which has already occurred since pre-industrial times. Such warming would cause severe disruptions to precipitation patterns, as well as to the frequency and intensity of some extreme weather events such as heat waves, and storm surges in coastal areas (Change 2013; Organization 2015). A 2 °C upper limit of temperature increase relative to pre-industrial levels has been internationally agreed in order to prevent severe and potentially catastrophic impacts from climate change. Reductions are necessary across countries and sectors. In order to stay below the 2 °C upper limit, it is estimated that global annual CO_2 emissions, which are currently at 5.2 tons per capita, need to be reduced to 1.6 tons per capita (Organization 2015).

Carbon dioxide is considered one of the primary causes of acid rain, along with sulfur dioxide and nitrogen oxides, as CO_2 interacts with water in the atmosphere, forming acid rain. Although the interaction of carbon dioxide with water produces a weak acid (carbonic acid), unlike sulfur and nitrogen oxides that produce strong acids (sulfuric and nitric acids) (Eldesouki et al. 2022; El-Khatib et al. 2004; El-Moneim et al. 2011), the increase in carbon dioxide emissions will exacerbate the situation (Singh and Agrawal 2007). Marine biologists have expressed grave alarm about the potential effects of ocean acidification on marine life. Alteration of one species or a group of species due to acidification will certainly negatively affect the ecosystem, especially food. Because calcification is anticipated to be hampered by increased seawater acidity, Marine calcifiers are thought to be particularly vulnerable. Additionally, acidified saltwater is regarded as "corrosive" and can lead to the dissolution of $CaCO_3$ minerals and the fragilization of calcareous structures. Furthermore, acidosis brought on by ocean acidification has the potential to impair numerous crucial physiological functions, including aerobic metabolism. In a result, metabolic depression slows down the energy production needed to maintain

calcification as well as several other biological processes and activities (Fabry et al. 2008; Pörtner 2008; Leung et al. 2022). The effects of acid deposition may currently be almost imperceptible, since 1850, the pH of seawater has already reduced by 0.1, and by 2100, it is expected to decrease by 0.3 (Figuerola et al. 2021), but with the increase in acidity, more and more species of plants and animals may decrease or even disappear. As the water's pH approaches 6.0, some crustaceans, insects, and plankton begin to disappear. As the pH approaches 5.0, significant changes occur for some fish group (Mehta 2010).

High CO_2 emission has both direct and indirect effects on human health. As carbon emissions are the main factor of climate change. Extreme heat waves, sea level rise, changes in precipitation that lead to floods and droughts, and powerful hurricanes can lead to some health problems and even death (Masson-Delmotte et al. 2021b; Ebi et al. 2018). For instance, worsening air pollution levels may have detrimental effects on cardiovascular and respiratory disorders (Mills et al. 2009). High carbon emissions also have a substantial negative impact on mental health and well-being (Ebi et al. 2021). According to certain studies (Ngarakana-Gwasira et al. 2016; Parham and Michael 2010), endemic malaria will become a bigger issue in the African highlands as a result of climate change. Temperature variations have an impact on the transmission of malaria by slowing or accelerating it. The amount of rainfall also has an impact on malaria transmission as it creates a lot of breeding grounds for mosquitoes (Mafwele and Lee 2022).

As we have previously stated, the results of increased carbon dioxide emissions will be disastrous for our planet, and therefore it is important to maintain acceptable levels of CO_2 in the atmosphere and not completely get rid of it because it has many benefits in preserving the normal temperature of our planet. On November 20, 2022, the twenty-seventh Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27), which was held in the Egyptian coastal city of Sharm el-Sheikh, concluded with some important key results that lead to a reduction in harmful carbon emissions, and the most important results are reducing the temperature to about 1.5 °C by encouraging strategies that lead to this, providing financing for losses and damages to vulnerable countries severely affected by floods, droughts and other climate disasters, a new focus on accountability when it comes to commitments made by sectors, companies and institutions as well as strengthening the actions taken by countries to reduce emissions greenhouse gases and adaptation to the inevitable effects of climate change, along with strengthening financing, technology and capacity building support needed by developing countries (Alayza et al. 2022).

The novelty of the review lies in presenting an integrated picture of carbon dioxide, including the various aspects that

surround the gas from the main sources that cause its emissions, such as fuel combustion, and some statistics related to carbon emissions such as most CO_2-emitting countries in the previous years. The research also deals with the most important strategies for controlling carbon emissions, like capturing and storing carbon dioxide using various technologies as well as converting it into synthetic fuels and products of economic value. This gives the reader a comprehensive view of carbon dioxide and thus leads to gaining more support and interest in this topic.

CO_2 emissions sources

Carbon dioxide emissions come from a variety of sources, including both natural and industrial sources. Decomposition, ocean release, and respiration are examples of natural sources. Human-caused sources include steel and cement industries, deforestation, and the consumption of fossil fuels such as coal, oil, and natural gas (Yin et al. 2020; Sher et al. 2021a, b). Globally, total carbon dioxide emissions from fossil fuel combustion and industrial activities in 2000 amounted to about 24.6 gigatons (Gt) CO_2 compared to 36.5 in 2021, an increase of about 48.4% (Metz et al. 2005; Atlas 2019; IEA 2021). By comparing the percentage of emissions resulting from the combustion of fossil fuels with those resulting from various industrial processes and biomass in 2020 as shown in Fig. 1 a, we find that CO_2 emissions from fossil fuels amounted to about 78%, while emissions from biomass were less than 1% (Ritchie et al. 2020). What makes carbon dioxide the main cause of global warming is that it is the main component of greenhouse gases, as Fig. 1 b shows that carbon dioxide has the largest proportion of greenhouse gases (79%), followed by methane (11%) and nitrous oxide (7%) (Hockstad and Hanel 2018). By comparing the emissions from the various energy sectors in the years 2000 and 2021 as shown in Fig. 1c, we find that the emissions resulting from coal are the largest compared to other sectors
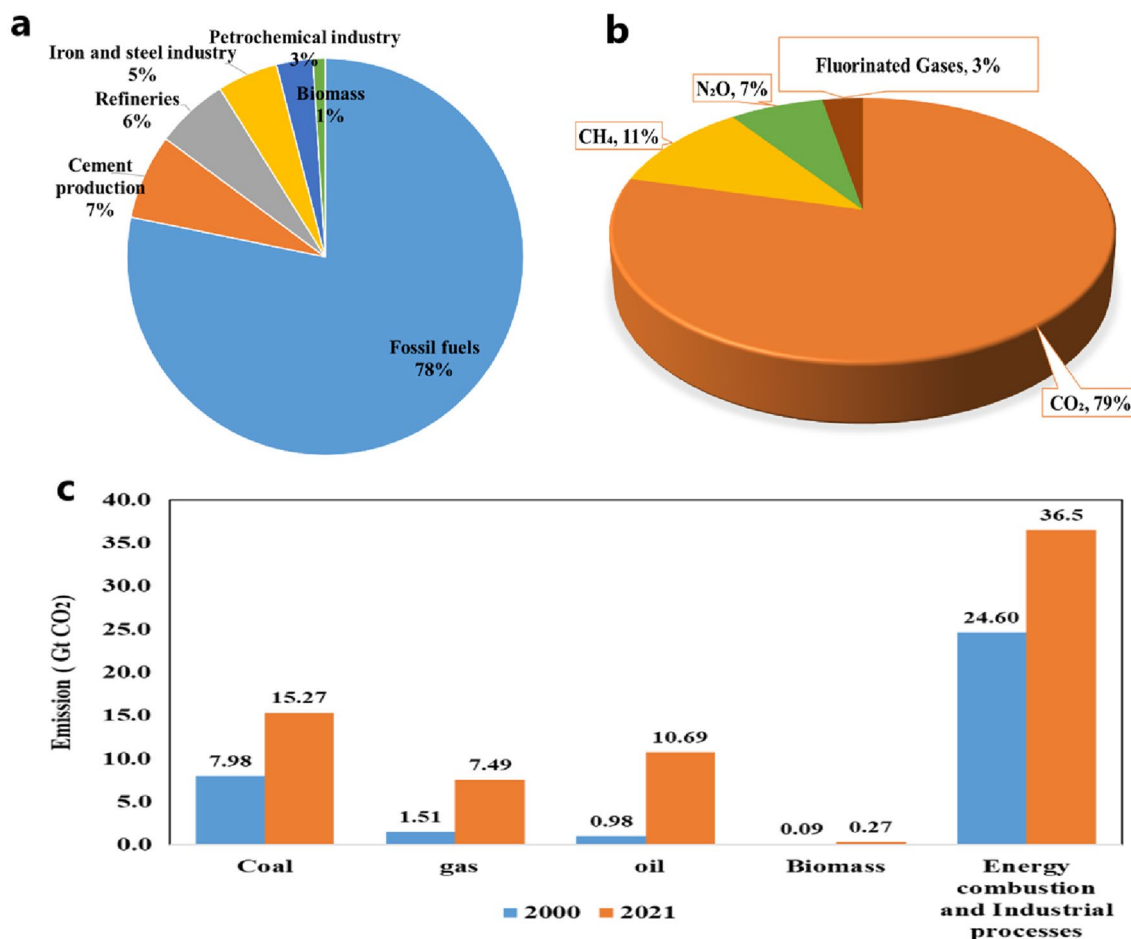
Fig. 1 **a** The percentages of CO_2 emissions from different sectors (Ritchie et al. 2020), **b** The percentage of greenhouse gas (GHG) components (Hockstad and Hanel 2018) and **c** Illustration of global carbon dioxide emissions from energy sources in 2000 and 2021 (Metz et al. 2005; IEA 2021)

of natural gas, crude oil and biomass in the two years, as the emissions resulting from coal doubled during the past two decades to reach 15 Gt CO_2. In 2021, emissions from coal were about twice as high as those from natural gas, and 30% more than those from crude oil (Metz et al. 2005; IEA 2021). The sectors of transportation, electricity generation, and industry are among the sectors that consume the most fuel and therefore emit the most carbon dioxide, especially in industrialized countries such as the United States of America, where carbon emissions from these sectors in 2020 amounted to about 80% of the total emissions as shown in Fig. 2, transportation represents about 33%, followed by
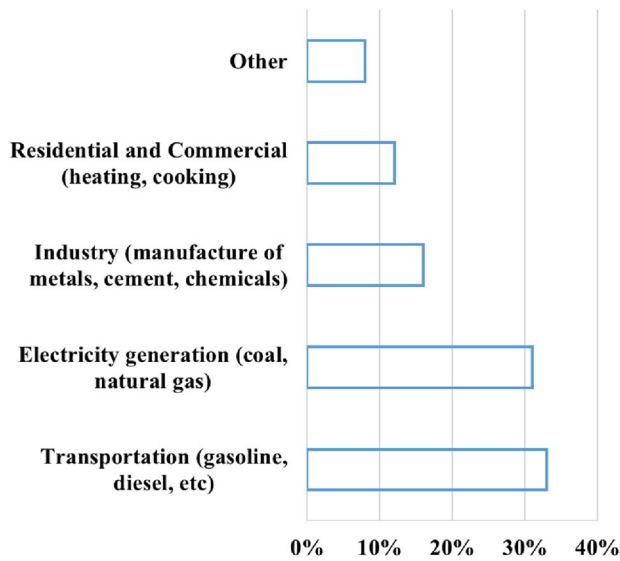

Fig. 2 CO_2 emission sources in the USA in 2020 (Solaymani 2019; Hockstad and Hanel 2018)

electricity generation by 31% (Solaymani 2019; Hockstad and Hanel 2018).

The major industrialized countries are the largest emitters of CO_2. Figure 3 shows the top ten countries that emitted the most carbon dioxide from 1990 to 2019. In 2019, China, whose emissions exceeded 10 Gt CO_2, was at the top of the list, and the United States of America came second with nearly half of this amount, then India with around 2.5 Gt CO_2, while Iran, South Korea, Indonesia and Canada, respectively, occupied the final four positions on the list, with a quantity that exceeded 0.5 Gt CO_2 (Agency 2021; Hockstad and Hanel 2018; Ritchie et al. 2020). Referring to the beginning of this period, the United States of America was in first place with emissions estimated at about 5.0 Gt CO_2, while China came second with emissions of about 2.4 Gt CO_2 (Atlas 2019). Table 1 represents the amount of emissions per capita in the countries that emit the most carbon dioxide during the past thirty years (Crippa et al. 2022), but it should be taken into account that the population varies from one country to another, and the population in the same country also varies over the years. For example, America ranks third in the world in terms of population, as it reached about 309 million in 2010. While the year 1990 was about 252 million (Crippa et al. 2020; Desa 2019). That is, the increase is about 57 million. In comparison, the amount of CO_2 emitted in 2010 amounted to 5.5 Gt CO_2 and 5.0 Gt CO_2 in 1990. Therefore, although the amount of emissions per capita decreased by about 2%, the actual emitted quantities increased by approximately 0.5 Gt CO_2.

Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon between the atmosphere, oceans, soils, plants and animals). Human activities are altering the carbon cycle—by adding more carbon dioxide to the atmosphere

Fig. 3 The top ten CO_2 emitter countries from 1990 to 2019 (Agency 2021; Hockstad and Hanel 2018; Ritchie et al. 2020)
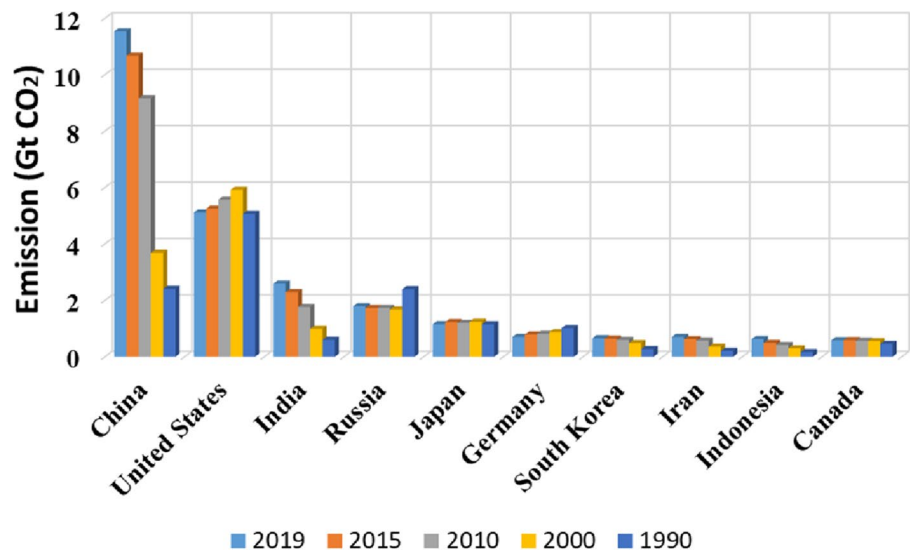
Table 1 CO_2 Emission per capita in the top emitted countries (Crippa et al. 2022)

	1990	2000	2010	2021
EU27	9.09	8.35	7.77	6.25
China	2.07	2.89	6.84	8.73
USA	20.07	21.29	18.05	14.24
India	0.69	0.94	1.41	1.9
Russia	16.23	11.43	12.11	13.52
Japan	9.41	9.82	9.54	8.6
Germany	12.88	10.78	10.11	8.06
South Korea	6.32	10.21	12.09	12.13
Iran	3.64	5.33	7.72	8.43
Indonesia	0.89	1.4	1.8	2.19
Canada	16.01	17.73	16.52	14.86

and affecting the ability of natural sinks, such as forests and soils, to remove and store carbon dioxide from the atmosphere. While CO_2 emissions come from a variety of natural sources, emissions associated with humans are responsible for the increase in the atmosphere since the industrial revolution that has led to global warming (Masson-Delmotte et al. 2021a). However, future projections indicate that by 2050, emissions will be reduced to about 50% of global carbon dioxide (Priddle 2002). This may relate to global awareness of the risks posed by high CO_2 emissions and the world trend to replace fossil fuels with clean energy such as hydrogen and methanol fuel.

It is important to implement certain economic policies, especially with regard to primary sources of carbon dioxide emissions, in order to reduce energy consumption from fossil fuel combustion. Some of these policies include discouraging the use of certain fuels and technologies, such as coal-fired power plants, gas boilers, and conventional internal combustion engine automobiles. Massive investment in infrastructure, including smart transmission and distribution networks, must also be planned for and encouraged by governments. Heavy industrial facilities must be equipped with Carbon Capture, Utilization and Storage techniques (CCUS) by 2030, new hydrogen-based plants must be constructed, and regulations banning the sale of new cars with internal combustion engines and replacing them with electric ones will lead to a significant reduction in transportation emissions. By 2050, all cars on the road must be powered by electricity or fuel cells. Increased reliance on low-emission fuels, for example, aviation should largely rely on biofuels and synthetic fuels. In terms of buildings, most old buildings and all new buildings must be modified to comply with clean energy uses as carbon–neutral. Globally, 1.6 Gt of CO_2 should be captured annually by 2030, rising to 7.6 Gt by 2050. Approximately 95% of all CO_2 captured will be kept in permanent geological storage, with the remaining 5% being

used to generate synthetic fuels (Bouckaert et al. 2021; Sher et al. 2021a, b).

CO_2 capture and storage

Carbon capture, use and storage can provide a major contribution to addressing the emissions. The technology options included in the Long-Term Strategy 2050 (Gielen et al. 2019; Bustos-Salvagno; Commission 2019) and "Sustainable Carbon Cycle Communications" (Plan 2018) are carbon dioxide capture from fossil fuel combustion or from industrial processes. The captured carbon is then either stored underground or used for the production of synthetic materials (fuels, chemicals, building materials). Carbon dioxide is captured from high sources such as power plants, steel and cement manufacturing plants by one of the following ways; chemical absorption, physical adsorption, membrane separation, cryogenic distillation and biofixation. The highly concentrated carbon dioxide is then compressed and transported through pipelines or ships to storage reservoirs (Svensson et al. 2004; McCoy and Rubin 2008) such as geologic formations (Anderson and Newell 2004) and oceanic storage(Adams and Caldeira 2008).

CO_2 capture technologies

There are three technological ways to capture CO_2 from power plants: pre-combustion capture, post-combustion capture and oxy-fuel capture as presented in Fig. 4. The post-combustion capture is useful for separating CO_2 from exhaust gases created by burning fossil fuels. The exhaust gases which contain mixture of CO_2 at concentration 13–15% (Wang et al. 2017), nitrogen and some oxides (SO_2, NO_2 and O_2) are firstly treated to remove particulate matter and the oxides of nitrogen and sulfur. Generally, they are in contact with a liquid solvent, such as amine solution. The amine selectively absorbs the CO_2, capturing more than 85% of the CO_2 and enabling nitrogen and oxygen to be released into the atmosphere (Ishaq et al. 2021). A CO_2-rich amine is regenerated by stripping the CO_2 out of the liquid with steam, allowing the lean amine to be recycled to the absorber while producing a concentrated CO_2 stream (Qureshi et al. 2021). Finally, CO_2 is compressed and cooled in liquid form (Basile et al. 2011). Compared to other fossil fuel power plants, natural gas combined cycle (NGCC) plants are regarded as being quite efficient in producing electricity (Rubin et al. 2005). As NGCC gives the same efficiency in power generation with carbon emissions less than half of those produced by coal-fired plants, but they still release a large amount of CO_2 into the atmosphere about 350 kg CO_2/MWh (Diego et al. 2017). Decarbonizing NGCC power plants using post-combustion technology is relatively

Fig. 4 Carbon capture pathways
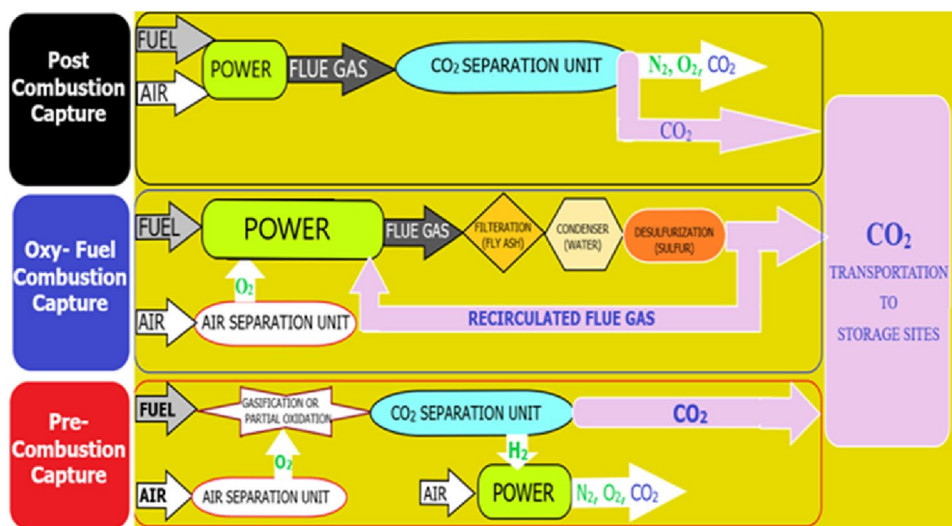
complex due to the high flue gas flow rate and low CO_2 intensity of ~ 3–4 vol% with a residual content of 20% O_2 and 77% N_2. Parallel and hybrid selective exhaust gas recirculation were investigated by (Qureshi et al. 2021), in which CO_2 was selectively recycled and mixed into the ambient air for the compressor input feed, lowering the flue gas flow rate and increasing CO_2 concentration at the capture plant's inlet. The performance results suggested that the CO_2 content of the hybrid configuration is increased to approximately 19 vol% and 13–14 vol% for the parallel configuration.

In the pre-combustion CO_2 capture, the hydrogen rich gas is used as a low carbon fuel in a combined cycle plant where syngas are produced by adding oxygen to the primary fuel, the process is called partial oxidation when the primary fuel is gaseous or liquid fuel and referred as gasification when it is applied to solid fuel.

$$\text{Partial oxidation:} \quad C_xH_y + x/2\, O_2 \rightleftharpoons xCO + (y/2)\, H_2$$
$$\Delta H_{CH4} = -36 \text{ kJ mol}^{-1} \tag{1}$$
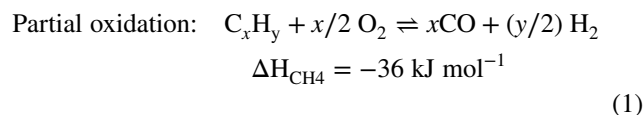
This partial oxidation is done using oxygen which separated from air. The syngas production is followed by the water–gas shift (WGS) reaction to convert CO to CO_2 and H_2 by the addition of steam. The concentration of CO_2 at the inlet separation stage can ranges from 15 to 60%.(Gazzani et al. 2013; Jansen et al. 2015).

$$\text{Water - gas shift:} \quad CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H = -41 \text{ kJ mol}^{-1} \tag{2}$$
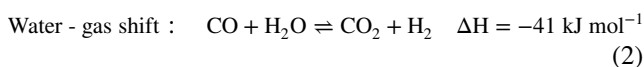
Oxy-fuel combustion is a new method of using enriched oxygen for fuel combustion with recycled flue gases to increase the CO_2 concentration in exhaust gases by up to 60–70%(Jurado et al. 2015) (compared to the post-combustion mode by about 13–15%) making it possible to separate
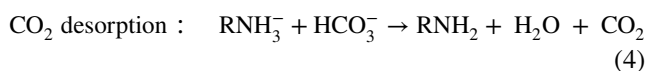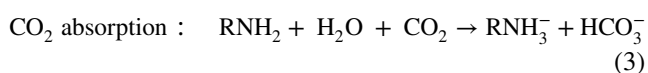
or capture pure CO_2 from the flue gas by means of low-temperature dehydration and desulfurization processes (Carpenter and Long 2017; Yang et al. 2008).

CO_2 separation technologies

In general, to economically separate CO_2 from power plants, a relatively pure high-pressure stream of CO_2 must be produced. The process of producing the carbon dioxide stream is referred to as separation process. CO_2 separation is a critical and important process for natural gas purification, flue gas recycling from thermal cracking, and greenhouse gas mitigation (Xu et al. 2021).

Absorption

Chemical absorption involves reaction between the absorbent substance (CO_2) and the solvents to form a rich liquid, then the rich liquid enters the absorption tower to heat and decompose CO_2 (Xie et al. 2020). Solvents that have proven efficiency in the process of carbon dioxide capture and storage belong to alkanolamine family such as monoethanolamine (MEA), diglycolamine (DGA), diethanolamine (DEA), di-isopropanolamine (DIPA), triethanolamine (TEA), N-methyldiethanolamine (MDEA), 2-amino-2-methyl-l-propanol (AMP), and 2-piperidineethanol (2-PE) (Benamor et al. 2012). Carbon dioxide is absorbed using amines to form a soluble carbonate salt. The absorber operates at a temperature below 60 °C and ambient pressure. This reaction is reversible and carbon dioxide can be released by heating the solution with the carbonate salt in a separate separation column. Decarbonization takes place at 120 °C and pressures range from 1.8 to 3 bar (Vega et al. 2018).

$$CO_2 \text{ absorption}: \quad RNH_2 + H_2O + CO_2 \rightarrow RNH_3^- + HCO_3^- \tag{3}$$

$$CO_2 \text{ desorption}: \quad RNH_3^- + HCO_3^- \rightarrow RNH_2 + H_2O + CO_2 \tag{4}$$

Despite MEA's efficacy in capturing CO_2 from flue gases. However, there are certain drawbacks, including major corrosion issues, a rapid degradation rate, a poor capacity, and a high energy consumption (Yeh et al. 2005; Zhang and Guo 2013). As an alternative to amines, ammonia is the most advantageous solvent for reducing CO_2 emissions and capturing CO_2 from power plants (Zhang and Guo 2017). (Ishaq et al. 2021) conducted a simulated model evaluation of an NH_3-based post-combustion CO_2 capture process for two process optimizations: a rich-solvent split process and split flow arrangement configurations. Compared to the reference, the NH_3-based process has shown a maximum reduction of 15.8% in re-boiler duty and an overall energy saving of 21.5% and the split flow arrangement is the most suitable modification to reduce the specific reboiler duty with aqueous ammonia and save energy by 32.8%.

Adsorption

Various materials such as zeolite and activated carbon (Kumar et al. 2020)**,** have been investigated as adsorbent materials for CO_2 separation and capture by adsorption process. Among these materials, activated carbon is the most common and most effective modified adsorbent due to its high surface area and large pore size. The adsorption method of CO_2 capture involves filling the packed column with an absorbent and a CO_2 carrying stream is passed through the column. The carbon dioxide is attracted toward the absorbent material and sticks to the surface of the absorbent material. After achieving the equilibrium, the desorption can be carried out to obtain pure CO_2 and renewable adsorbent by raising the temperature (Krishnaiah et al. 2014).
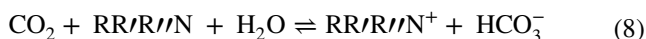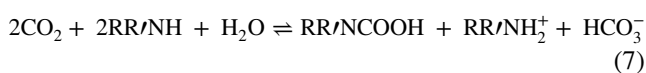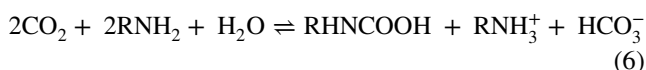
Membrane separation

In membrane separation processes, the membrane acts as a selective barrier allowing relatively free passage of one component while retaining another. Polymeric membranes are of particular economic importance due to the low cost of the material and ease of large-scale manufacture. In a typical membrane gas separation process, the partial pressure of the penetrating gases is represented as the driving force, as gas molecules are first adsorbed on the upper side of the membrane, then diffuse across the membrane and finally adsorb on the lower side of the membrane. The membrane separation process can be explained by two mechanisms, the solution-diffusion mechanism, and the facilitated transport mechanism. The mechanism of solution-diffusion depends mainly on permeability and selectivity. Permeability (P_A) is a product of the solubility coefficient (S_A) and the diffusion coefficient (D_A), and is given by Eq. 5 (Ebnesajjad 2016; Wu 2019).

$$P_A = S_A \times D_A \tag{5}$$

The solubility of gas molecules in a membrane is directly proportional to gas condensability (characterized by the critical temperature) and interactions of gas molecules with the membrane matrix. Gas diffusion through the membrane is controlled by void space between polymer chains. Since the critical temperature of CO_2 (31 °C), is greater than other light gases (N_2 (−147 °C), CH_4 (−82 °C), H_2 (−240 °C)). Therefore, the solubility of CO_2 gas is the highest leading to CO_2 being the much more permeable gas (Wang et al. 2016). In facilitated transport mechanism, the reactive carriers in the membrane react reversibly with small molecules and hence, facilitate the transporting process. The CO_2 hydration reaction with primary and secondary amine gives carbamate ion, however, with tertiary amine produces bicarbonate as the following reactions:

$$2CO_2 + 2RNH_2 + H_2O \rightleftharpoons RHNCOOH + RNH_3^+ + HCO_3^- \tag{6}$$

$$2CO_2 + 2RR\prime NH + H_2O \rightleftharpoons RR\prime NCOOH + RR\prime NH_2^+ + HCO_3^- \tag{7}$$

$$CO_2 + RR\prime R\prime\prime N + H_2O \rightleftharpoons RR\prime R\prime\prime N^+ + HCO_3^- \tag{8}$$

The CO_2 separation performance of the membranes is affected by the CO_2 carrier reaction kinetics. If carriers have a very strong affinity for CO_2, they will react almost irreversibly, and the CO_2 will not be able to be released. If the carriers react slowly with CO_2, the membrane will easily become saturated with carbon dioxide and easy transfer will not occur. Ideally, efficient facilitated transport requires a balance of fast responses (Wang et al. 2016).

Cryogenic distillation

In the cryogenic distillation, the gases mixture is separated using high pressure and low temperature. The stream gas is first dehydrated and then cooled with refrigeration to a temperature ranges from −100 to −135 °C followed by separation of solid CO_2 from the lighter gases. By this process, methane, ethane, propane and hydrogen sulfide can also be separated (Stewart and Arnold 2011). One of the most important features of this process is the ability to separate a large amount of carbon dioxide gas, which can reach 90–95%, as the gas is compressed into a liquid. However, the main problem is the amount of energy consumed, which was estimated at about 600–650 kW to recover one ton of CO_2 in liquid form (Hanif et al. 2022).

Biofixation

Microalgae are microscopic organisms found in sea and fresh water. They can be classified into eukaryotic microorganisms or prokaryotic cyanobacteria (blue-green algae), and more than 25,000 species have been isolated from these organisms. These microorganisms carry out photosynthesis, an important natural mechanism for reducing the concentration of carbon dioxide in the atmosphere (Vale et al. 2020). Microalgae are considered attractive bio-factories for carbon dioxide sequestration and production of value-added products such as biofuels and food (Ryan et al. 2009; Harun et al. 2010). The ability of CO_2 capture by microalgae depends on many parameters such as microalgae species, cultivation system, temperature, pH, turbidity and salinity. One of the most important advantages of using microalgae is the ease of the method, as well as energy savings over other methods (Onyeaka et al. 2021). The results of some studies showed that the Chlorella sp. has the best ability to absorb CO_2 with high efficiency (Iglina et al. 2022). The majority of the microalgae are photoautotrophic as they convert inorganic CO_2 into carbohydrates via photosynthesis process (Prasad et al. 2021). In the photoautotrophic process, the most common pathway for synthesizing organic compounds from carbon dioxide is the reductive pentose phosphate (Calvin) cycle shown in Fig. 5 in which the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) plays acritical role in CO_2 sequestration. The enzyme catalyzes the reaction of CO_2 with ribulose-1,5-bisphosphate (RuBP) to form 3-phosphoglycerate (PGA) which is converted into the carbohydrate glyceraldehyde-3-phosphate. Some of this product exits the pathway that will be used for the synthesis of more complex carbohydrates or other carbon compounds
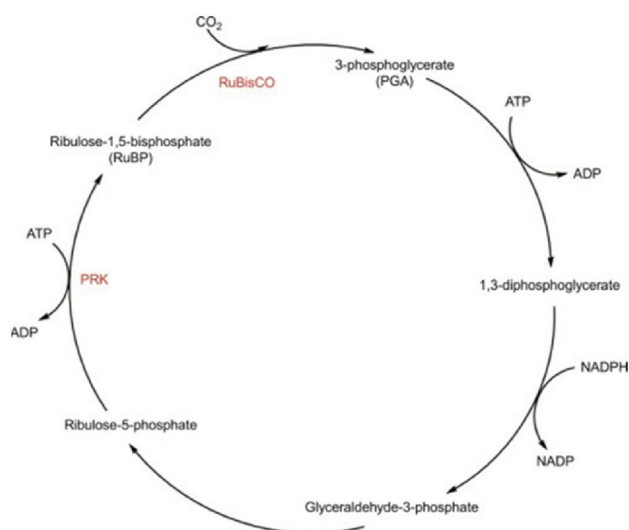

Fig. 5 Calvin cycle (Senatore et al. 2020)

and the rest is converted back into RuBP (the substrate for the initial CO_2 fixation reaction (Senatore et al. 2020).

Projects are now being supported to develop CO_2 capture technologies in more than 30 countries. For instance, a total capability to capture around 15 Mt CO_2 annually by 2030 may arise from more than ten projects throughout Southeast Asia, most of which have been announced since January 2020. Regarding North America, the USA has over 80 target projects prepared for execution by 2030 and may show a roughly fivefold increase in its annual capacity of carbon dioxide capture, from more than 20 Mt CO_2 to more than 100 Mt CO_2. There are at least four projects in the Middle East that are in various stages of development. The North Field East LNG project in Qatar will increase the country's CCUS capacity by 2050 from more than 2 Mt CO_2 to 5 Mt CO_2 per year (Budinis et al. 2022).

CO_2 conversion

Converting CO_2 into valuable products is a huge challenge as it aims to eliminate millions of metric tons of carbon dioxide, which are emitted annually from power plants and lead to air pollution. The world is currently following some strategies to preserve the environment from the emissions that posed a threat in the past decades. These strategies include the relying on clean and renewable energy as an alternative to fossil fuels, the main cause of carbon dioxide emissions. In another direction, the efforts of researchers and scientists to find new ways and catalysts to achieve the largest conversion rate of carbon dioxide gas and produce fuels as well as industrial materials such as polymers and plastics. The process of converting carbon dioxide is not free from some difficulties, as carbon dioxide consists of one carbon atom covalently bonded by two bonds with two oxygen atoms. The bonds between oxygen and carbon atoms are very strong, which makes the molecules more stable, and to conduct reactions on carbon dioxide, these stability must be weakened (Aresta et al. 2014). In order to achieve this goal, three main obstacles must be overcome: large energy inputs must come from low carbon sources to avoid more carbon dioxide emissions, active catalysts to reduce the activation energy of carbon dioxide conversion processes and achieve the most conversion rate, and finally, suitable reaction conditions represented by high temperatures and pressures to weaken the stability of carbon dioxide (Alper and Orhan 2017; Kamkeng et al. 2021). The following discusses the Fischer–Tropsch technology as one of the important methods that are used in the process of producing valuable materials from carbon dioxide, as well as several valuable products from CO_2 conversion process.

Fischer–Tropsch technology

It was developed in the mid-1920s in Germany to produce liquid fuels from coal. What gives this technology the advantage is that it can produce types of liquid fuels at competitive prices for petroleum today (Suppes and Storvick 2016). Fischer Tropsch is a gas-to-liquid polymerization technology to convert carbon monoxide and hydrogen into liquid hydrocarbon fuels. It is an exothermic process through the use of a metal catalyst that causes polymerization (Darmawan and Aziz 2022), according to reaction (9).

$$nCO + (2n + 1)H_2 \rightarrow CH_{2n+2} + nH_2O \qquad (9)$$
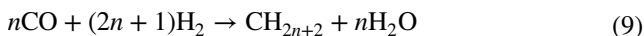
It is clear from the previous description that the process of Fischer–Tropsch depends mainly on carbon monoxide, so to use this method for CO_2, carbon dioxide must first be converted to carbon monoxide (Garba et al. 2021; Rashed et al. 2021). This is possible through the production of Syngas (CO, H_2) using the reverse water gas shift (RWGS) process as described in reaction (10). This reaction is thermodynamically favored at elevated temperatures (Hannula et al. 2020).

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H = -41.2 \text{ KJ/mol} \qquad (10)$$

Since the development of effective catalysts enhances the RWGS pathway, selectivity can be increased also by optimizing the operating conditions such as temperature, pressure, H_2/CO_2 ratio, or amount of catalyst (Portillo et al.

2023). There are two proposed mechanisms for RWGS reaction: the associative and redox mechanisms. In a redox process, CO_2 is reduced on an electron donor's surface to give CO and the electron donor which could be a metal or an oxygen vacancy in a reducible oxide is oxidized. Water is then produced when H_2 reduce the active center again to its primary state. The associative mechanism involves the reaction between CO_2 activated species on the surface and H dissociated species to produce reaction intermediates, which then break down to form the reaction products (González-Castaño et al. 2021). Depending on the catalyst, temperature, and type of process employed, hydrocarbons ranging from methane to higher molecular paraffins and olefins can be obtained (Rashed et al. 2022). Also, small amounts of low molecular weight oxygenates are produced (such as alcohol and organic acids). Over the years, three types of Fischer–Tropsch reactors have been used as described in Table 2 and Fig. 6; fixed bed reactor, slurry reactor, and fluidized bed reactor.

Fixed bed reactor

This type of reactor is used in low and high temperature Fischer–Tropsch processes where it operates between 180 and 350 °C, at pressures ranging from 10 to 45 bar (Botes et al. 2011). The process is characterized by the reaction of different gases on the surface of the catalyst placed in a fixed position inside the reactor. The feed gas follows the path of

Table 2 Comparison of various Fischer–Tropsch reactors

	Fixed bed reactor	Slurry reactor	Fluidized bed reactor
Temperature	180–350 °C Botes et al. (2011)	220–290 °C Meng and Nawaz (2022), Saeidi et al. (2014)	> 250 °C Saeidi et al. (2014), Dahlhoff et al. (2001), Bhaskar et al. (2011) Gunjal and Ranade (2016)
Pressure	10–45 bar Botes et al. (2011)	20–30 bar Saeidi et al. (2014)	1–20 bar Dahlhoff et al. (2001), Saeidi et al. (2014), Suleiman et al. (2013), Gunjal and Ranade (2016)
Advantages	Simple and flexible Easy catalyst separation Saeidi et al. (2014) Easy maintenance The volumetric loading of the catalyst is high	Catalyst activity can be maintained at a constant level by addition and withdrawal of catalyst Saeidi et al. (2014) Suitable for large-scale designs Low Pressure drop Wang and Economides (2009) Effective Temperature control Wang and Economides (2009)	Possible catalyst regeneration Gunjal and Ranade (2016) Good catalyst handling Saeidi et al. (2014) Good temperature controlling Saeidi et al. (2014) Effective mass transfer Dhyani and Bhaskar (2019) Uniformity in product quality Gunjal and Ranade (2016)
Disadvantages	Insufficient heat removal Guettel and Turek (2009) High pressure drop Guettel and Turek (2009) Catalyst sintering Difficult catalyst handling Higher operation cost	Lower volumetric loading of the catalyst compared to fixed bed reactor Catalyst separation from the liquid products is needed Guettel and Turek (2009 Avci and Önsan (2018) High viscosity of slurries Wang and Economides (2009) Low mass transfer in the liquid Wang and Economides (2009)	Precise control is needed Saeidi et al. (2014) Erosion is possible Gunjal and Ranade (2016)
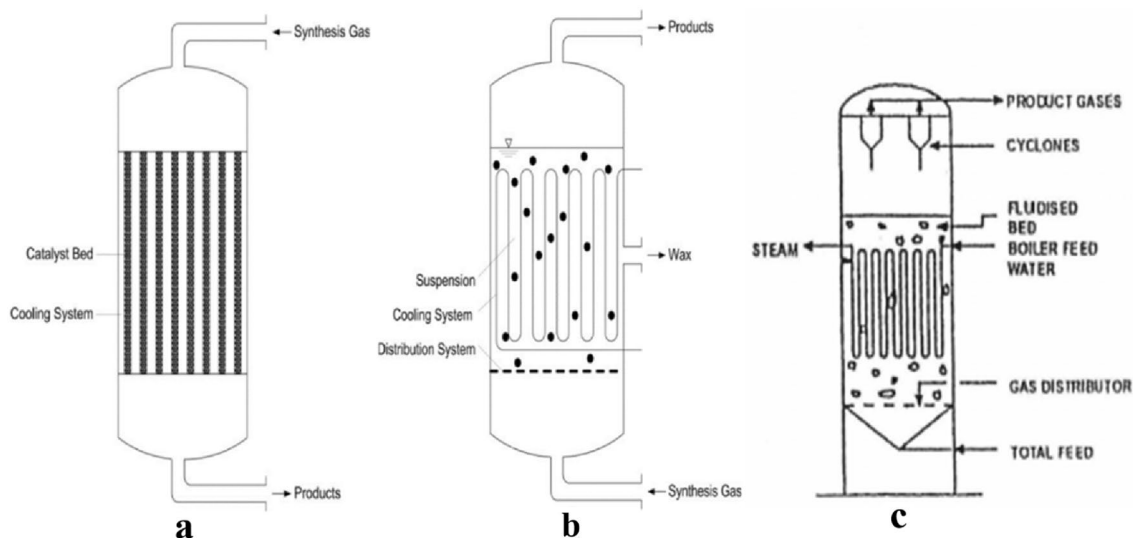
Fig. 6 Schematic diagram of **a** Fixed bed reactor, **b** Slurry reactor (Guettel et al. 2008) and **c** Fluidized bed reactor (Dry 2002)

Fig. 7 Photo image from catalysis laboratory showing a 1-inch stainless steel fixed bed reactor and online gas chromatography used for gas conversion at Graphene Center of Excellence for electronic and energy applications, Egypt-Japan University of Science and Technology, Alexandria, Egypt

a heat carrier that allows for control of different temperature profiles around the fixed tubular catalysts as shown in Fig. 7 (Nelabhotla et al. 2021; Rashed et al. 2023). Fixed bed reactors are simple and flexible, however, there are some disadvantages such as high cost and to avoid a high-pressure drop in the reactor tubes, large catalyst particles are required that lead to catalytic activity reduction (difficulty diffusion of reactants in the catalyst particle core), in addition, low heat transfer from the catalyst bed, and temperature change in the tubes make it difficult to control the production process (Schubert et al. 2001; Worstell 2014).

Slurry reactor

In order to get around the problems with fixed bed reactors, slurry reactors were created. The slurry reactor is easier to design and much cheaper. Also, it is characterized by rapid heat removal, and because the slurry phase is well mixed, the temperature inside the reactor is more stable. This means that greater temperatures can be reached without the risk of catalyst sintering (Rauch et al. 2013; Nasser et al. 2018). Additionally, raising the slurry concentration will result in more large bubbles being formed, which will boost the reactor's productivity (Inglezakis and Poulopoulos 2006). A low pressure drop, wide catalyst surface area (Reay et al. 2013), simple catalyst removal, and low catalyst consumption are further significant benefits (Wang and Economides 2009). In slurry reactors, the mobile catalytic (solid) phase coexists with the gas and liquid phases. Depending on the procedure, the stages might play a variety of roles. The gas phase can be one of the reactants or products, or an inert substance used to stir a liquid and solid mixture. Similarly, the liquid phase can participate in the catalytic reaction or act as an inert medium for the contact of the gas phase and solid catalyst (Avci and Önsan 2018).

Fluidized bed reactor

In fluidized bed reactors, the catalyst is positioned on a distributor plate on which a fluidized gas is passed, carrying the particles in a fluid state. This eliminates some of the issues with fixed bed reactors. As a result, catalysts are more available because they are well mixed in fluid and have a larger surface area to react on (Rajmohan et al. 2020; Zhang et al. 2019). Fluidized bed reactors also employ a heat carrier
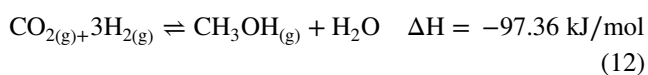
made up of small inorganic particles, which are very efficient at providing high heat-transfer rates while maintaining uniform bed temperatures (Gunjal and Ranade 2016; Guda et al. 2015).

Valuable products

The products of the carbon dioxide conversion process attract the attention of researchers to try to find methods and catalysts that help in this process, as it is possible to convert CO_2 to a substance of great industrial importance from fuels and monomers to polymers and plastics (Hassan et al. 2020). To simplify the idea, we will mention some practical examples of CO_2 conversion products.

Oxygenates

One of the top five most traded chemicals in the world is the simple oxygenated hydrocarbon methanol, or CH_3OH (Verhelst et al. 2019). It is an easily available biodegradable and widely used chemical, which can be used in production of various value-added chemicals (Shee et al. 2022). Methanol is used as a volatile organic solvent in factories. It is also the most commonly used fuel in direct methanol fuel cells (DMFCs) (Cheshideh et al. 2022). The process of producing methanol from CO_2 is an important process because it helps reduce carbon emissions. The main methanol production reactions are (Previtali et al. 2020):

$$CO_{(g)} + 2H_{2(g)} \rightleftharpoons CH_3OH_{(g)} \quad \Delta H = -136.9 \text{ kJ/mol} \quad (11)$$

$$CO_{2(g)} + 3H_{2(g)} \rightleftharpoons CH_3OH_{(g)} + H_2O \quad \Delta H = -97.36 \text{ kJ/mol} \quad (12)$$

The main factors in this process are the catalytic activity of the catalysts and the reaction conditions of temperature and pressure. The catalytic activity is assessed by the selectivity of the catalyst to methanol and the rate of methanol production. Other gases are often produced from the conversion process, such as carbon monoxide and methane (Xiong et al. 2019). The higher the selectivity and rate of methanol production, the higher the efficiency of the catalyst as shown in Table 3. Methanol can often be used in blends or in pure form in internal combustion engines in the transportation sector. Currently, M85 (a mixture of 85 vol% methanol and 15 vol% gasoline) or M100 (pure methanol) can be used in the spark-ignited combustion engines of light-duty vehicles in China. Methanol can currently be blended up to 3% in gasoline, according to the European standard DIN EN 228, and it is widely regarded as a viable future fuel for marine applications (Schorn et al. 2021).

Dimethyl ether (DME) is one of the simplest ethers, consisting of two methyl group attached to an oxygen atom. It is not a toxic or carcinogenic compound and has a boiling point of 25 °C, however, it is liquid at room temperature under relatively low pressure (≈0.5 MPa) (Catizzone et al. 2017). DME has been noticed as useful and pure fuels for transportation, domestic applications, and power production. With its high cetane number, it can be used as an alternative to diesel fuel (Shikada et al. 2007; Obora and Ishii 2014). What gives DME some advantages that it is safe in storage i.e., it does not form explosive peroxides. Since it does not contain a C–C bond and consists of 35% oxygen, its combustion products are carbon monoxide and unburned hydrocarbon emissions with no emission of toxic gases such as NO_x, which are lower than that of natural gas (Azizi et al. 2014). In addition, DME is highly recommended as an environmentally friendly and green refrigerant as it has zero ozone depletion potential and lower global warming potential compared to conventional chlorofluorocarbons (CFCs, Freon) (Lei et al. 2011). Various precursors, such as natural gas, crude oil, leftover oil, coal, and waste products, can be used to produce DME (Rahimpour et al. 2012). There are two popular methods for producing DME; the first method is called the indirect method and consists of two steps with two reactors, where the syngas (CO, H_2) are converted to methanol first, and then methanol is converted to DME as shown in reaction (11) and (13) (Azizi et al. 2014).

Table 3 Comparison of the catalytic activity of some different catalysts

Catalyst	Temperature °C	Pressure MPa	MeOH		CO_2/ H_2 feed ratio	method	References
			Selectivity%	Production%			
MoS_2	180	5.0–6.0	94.3	12.0	1:3	Fixed-bed reactor	Hu et al. (2021)
Ir/In_2O_3	300	5.0	>70.0	17.7	1:4	Tubular microreactor	Shen et al. (2021)
$Ni-In_2O_3$	300	5.0	>54.0	18.47	1:4	Fixed-bed reactor	$Ni-In_2O_3$ Jia et al. (2020)
Re/TiO_2	150	5.0	82.0	–	1:3	Stainless autoclave	Ting et al. (2019)
$Pd/In_2O_3/SBA-15$	260	5.0	83.9	12.6	1:4	Fixed-bed reactor	Jiang et al. (2020)
$10Cu/ZnCr-3.5$	300	2.0	48.0	11.0	1:3	Fixed-bed reactor	Ting et al. (2019)

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \quad \Delta H^{\circ}_{298K} = -23 \text{ KJ/mol} \tag{13}$$
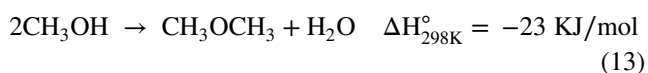
The direct method by which DME can be produced directly from syngas in a single reactor as presented in reaction (14) (Ng et al. 1999).

$$3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2 \tag{14}$$
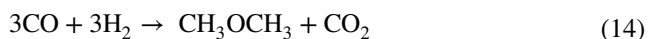
One of the most promising modern fuel sources for low-temperature proton exchange membrane fuel cells is formic acid (HCOOH). It is slightly toxic liquid (Robles 2005) and easy to store, providing an additional economic incentive to develop commercially viable direct formic acid fuel cell (Rojas-Andrade and Chen 2018). Formic acid has a wide range of commercial applications, including industry, grass silage, finishing, leather tanning, textile dyeing, natural rubber, food additives, drilling fluids, and a variety of chemical processes (Kawanami et al. 2017). As presented in Fig. 8, different chemicals can be used for formic acid preparation. Carbon monoxide can be used to produce formic acid and this considers the commercial BASF production route. The process contains two reactions. Using a strongly basic sodium methoxide catalyst, CO reacts with methanol to produce methyl formate in the first step then excess water is used to hydrolyze the methyl formate to formic acid. Direct hydrogenation of carbon dioxide in dimethyl sulfoxide (DMSO) with a homogeneous ruthenium catalyst yields 1.9 M formic acid (Moret et al. 2014).

Hydrocarbons

These are organic compounds that contain both hydrogen and carbon. Most hydrocarbons such as gasoline are by-products of crude oil, and are therefore called petroleum distillates. Many products, including cosmetics, household chemicals, pesticides, fuels, and essential oils, use
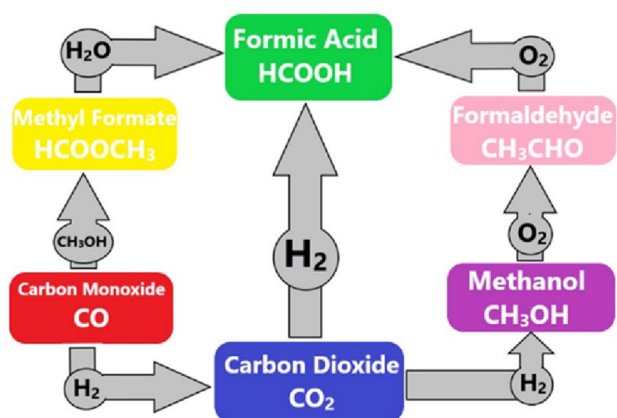

Fig. 8 Formic acid production by different ways

hydrocarbons as solvents and thinners. There are two types of hydrocarbons: aliphatic (straight chain structures like propane) and aromatic (cyclic structures, such as toluene) (Cubo 2010). In addition to the importance of hydrocarbons as fuels and solvents, one of the most important industrial applications is the production of many polymers and plastics from hydrocarbon monomers such as ethylene and propylene. So, the production of hydrocarbons from the conversion of carbon dioxide represents an industrial leap and a technological transformation. This is because the decline in crude oil production will threaten some industries, especially petrochemical industries, which depend mainly on crude oil refining products.

The simplest hydrocarbon molecule i.e., methane, is a gas with no color or smell, and widely distributed in nature. It makes up the majority of natural gas, which is a mixture of approximately 75% CH_4, 15% ethane (C_2H_6), and 5% other hydrocarbons such propane (C_3H_8) and butane (C_4H_{10}) (Pegov 2008). Despite the minor presence of atmospheric methane, it is crucial for regulating the chemistry of the atmosphere by regulating the levels of ozone in the troposphere and acting as a significant sink for hydroxyl radicals in the stratosphere (Scranton and de Angelis 2001). Various supported catalysts have received a lot of attention in CO_2 methanation over the last three decades such as catalysts based on Ru, Rh, Ni, Fe, Co, or Pd. The active metals have been supported by carriers or supports such as SiO_2, Al_2O_3, ZrO_2, La_2O_3, CeO_2, TiO_2, MgO, zeolites and carbon compounds (Janke et al. 2014a; Borgschulte et al. 2013; Chang et al. 2001; Song et al. 2010). R. Farrauto and co-workers studied the catalytic activity of 10% Ru/γ-Al_2O_3//monolith on the conversion of CO_2 to methane (Janke et al. 2014a). The reaction mixture was 4 vol.% CO_2 and 16 vol.% H_2. At 217 °C and GHSV = 4720 h^{-1}, the Ru/γ-Al_2O_3 catalyst was subjected to eight start-up/shut-down cycles with varying reaction times ranging from 1 to 24 h. At low hydrogenation temperatures, excellent selectivity to methane and CO_2 conversions was achieved under low space-velocity conditions. As a result, the authors proposed that Ru/γ-Al_2O_3 be used for wash-coated on a heat exchanger to remove the heat liberated. Another research conducted by Sastre and his researchers (Sastre et al. 2014) indicates the possibility of obtaining a conversion rate of over 90% using Nickel supported on silica − alumina and a CH_4 selectivity above 95% using sunlight derived from visible light photo response according to the following reaction.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \Delta H = -165 \text{ kJ/mol} \tag{15}$$
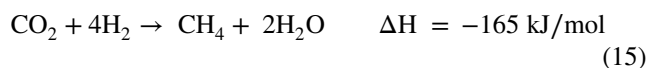
Gasoline is a middle distillate fraction of crude oil that has been blended with a number of other hydrocarbon and polymer compounds originating from relatively light fractions (C4–C12). Originally, gasoline was a byproduct

of the refinery process used to make kerosene from petroleum. It quickly became the preferred automobile fuel due to its high combustion energy (Stauffer et al. 2008; Kaltschmitt and Deutschmann 2012; Lois et al. 2003; Bergendahl 2007). Because of the great importance of gasoline, the process of converting CO_2 into gasoline attracted the attention of scientists, so the researchers focused their research on finding catalysts capable of carrying out this process. Jian Wei (Wei et al. 2017) showed that by using Na-Fe_3O_4/HZSM-5 catalyst and a ratio of 1 of feed gas H_2/CO_2, high selectivity for gasoline (C5–C11) of 78% and for CH_4 of no more than 4% with CO_2 conversion of 22% were achieved. This could be explained by the catalyst's multifunctionality, which includes three types of active sites with complementary and compatible properties. During CO_2 hydrogenation, CO_2 is first reduced to CO by H_2 via RWGS on Fe_3O_4 sites, then CO is hydrogenated to α-olefins via FTS on Fe_5C_2 sites. The olefin intermediates produced by the iron-based catalyst diffuse to the zeolite acid sites, where they undergo acid-catalyzed reactions (oligomerization, isomerization, and aromatization), resulting in the formation of isoparaffins and aromatics that diffuse from the zeolite pores. Another research team has investigated the capability of a multifunctional catalyst made of a mixture of zinc-modified zeolite beta and a methanol producer (InCo) to transform CO_2 into gasoline. A combination of isoparaffinic hydrocarbons was created with a CO_2 conversion of more than 15% and up to 85% iso paraffin selectivity among hydrocarbons (Dokania et al. 2021).

The challenge in converting carbon dioxide to fuel is that it is energy intensive. If we rely on renewable sources to generate energy, we will face two issues: energy storage and fuel transportation. Wind and solar power, for example, require significant energy storage to ensure that electricity can be produced when there is no wind or sun. The most significant advantages of fossil fuels appear here, i.e., their high energy density and ease of storage and transportation (Smit et al. 2014). Another obstruction is the high cost of carbon capture and storage technologies. As well, this technology may not play a sufficient role in rapidly reducing global emissions needed to limit warming to 1.5 °C above pre-industrial levels. To overcome this problem, the development of CCS must be directed in partnership with some sectors such as the petroleum industry as well as iron and cement companies to drive innovation and reduce costs of carbon dioxide capture and storage (Irlam 2017; Hastings and Smith 2020).

Conclusion

There is no doubt that CO_2 gas represents a big problem if it exceeds its permissible normal levels (1.6 tons per capita), but this does not mean that carbon dioxide should be completely eliminated, as CO_2 is the most important greenhouse gas and its presence in the atmosphere trap heat near the earth, which helps the earth to retain some of the energy it gets from the sun, so that it does not lose all the energy to space. The main problem is the increase in its levels, which poses a danger because it leads to global warming and rises the temperature of the planet. Therefore, it is necessary to control the CO_2 gas. For this reason, scientists rushed to recycle CO_2 for two purposes: the first goal is to reduce CO_2 emissions, allowing it to be preserved within safe limits, and the second goal is to work on using it in important industrial applications like fuel as an alternative to fossil fuels, as well as producing some commercially important products such as methanol, diethyl ether and other solvents. For utilizing CO_2, systems for both capturing and storing CO_2 have been developed, then comes the final stage, which is converting it into valuable products and this depends on the catalysts, which are the process' principal driving force. Given the importance of this topic, future prospects should include more studies to give answers to some inquires such as which of the methods that have been mentioned are most appropriate for separating carbon dioxide, if we have to maintain carbon dioxide at normal levels, how will we maintain the balance between the quantities emitted and consumed, and can we really completely abandon fossil fuels, the main cause of carbon dioxide emissions, and move toward safer alternatives. The world is not far from the negative effects of climate change. Therefore, 198 countries meet annually through the "Conference of the Parties to the United Nations Framework Convention on Climate Change" (COP) to try to find ways to preserve the environment from climate change and to help developing countries combat the effects of climate change. It can take decades to bring new energy technologies to market, but due to the necessity of achieving net-zero emissions globally by 2050, progress must be made considerably more quickly. The government's role includes increasing funding for research and development to achieve zero emissions, providing networks for knowledge exchange, and protecting intellectual property, as well as assisting companies to innovate and invest in infrastructure, and increasing people's awareness of clean energy has become a necessity in our current era to maintain safe levels of emissions. Perhaps it is more likely that the near future will remain largely dependent on fossil fuels as the main source of energy supply, but it is certain when fossil fuels

run out, the world will turn to alternatives. There is a need to produce alternative fuels, and one of the important options available is CO_2 conversion.

Declarations

References

Adams EE, Caldeira K (2008) Ocean storage of CO^2. Elements 4:319–324

Agency, US Environmental Protection (2021) Inventory of US greenhouse gas emissions and sinks: 1990–2019. In.: US Environmental Protection Agency Washington (DC)

Alayza, Natalia, Bhandari P, Burns D, Cogswell N, de Zoysa K, Finch M, Fransen T, González ML, Krishnan N, and Langer P (2022) COP27: Key takeaways and what's next

Alper E, Orhan OY (2017) CO_2 utilization: developments in conversion processes. Petroleum 3:109–126

Anderson S, Newell R (2004) Prospects for carbon capture and storage technologies. Annu Rev Environ Resour 29:109–142

Aresta M, Dibenedetto A, Angelini A (2014) Catalysis for the valorization of exhaust carbon: from CO_2 to chemicals, materials, and fuels: technological use of CO_2. Chem Rev 114:1709–1742

Atlas, IEA Energy (2019) IEA Energy Atlas. In.: International Energy Agency. http://energyatlas.iea.org

Avci AK, Ilsen Önsan Z (2018) 2.16 catalysts. In: Dincer I (ed) Comprehensive energy systems. Elsevier, Oxford

Azizi Z, Rezaeimanesh M, Tohidian T, Rahimpour MR (2014) Dimethyl ether: a review of technologies and production challenges. Chem Eng Process 82:150–172

Basile A, Gugliuzza A, Iulianelli A, Morrone P (2011) 5 - Membrane technology for carbon dioxide (CO_2) capture in power plants. In: Basile A, Nunes SP (eds) Advanced membrane science and technology for sustainable energy and environmental applications. Woodhead Publishing

Benamor A, Aroua MK, Aroussi A (2012) Kinetics of CO_2 absorption into aqueous blends of diethanolamine and methyldiethanolamine. In: Aroussi A, Benyahia F (eds) Proceedings of the 3rd gas processing symposium, Elsevier, Oxford

Bergendahl J (2007) Chapter 13—environmental issues of gasoline additives–aqueous solubility and spills. In: Letcher TM (ed) Thermodynamics, solubility and environmental issues. Elsevier, Amsterdam

Bhaskar T, Bhavya B, Singh R, Naik DV, Kumar A, Goyal HB (2011) Chapter 3—thermochemical conversion of biomass to biofuels. In: Pandey A, Larroche C, Ricke SC, Dussap CG, Gnansounou E (eds) Biofuels. Academic Press, Amsterdam

Borgschulte A, Gallandat N, Probst B, Suter R, Callini E, Ferri D, Arroyo Y, Erni R, Geerlings H, Züttel A (2013) Sorption enhanced CO_2 methanation. Phys Chem Chem Phys 15:9620–9625

Botes FG, Dancuart LP, Nel HG, Steynberg AP, Vogel AP, Breman BB, Font Freide JHM (2011) 11—middle distillate fuel production from synthesis gas via the Fischer–Tropsch process. In: Khan MR (ed) Advances in clean hydrocarbon fuel processing. Woodhead Publishing

Bouckaert S, Pales AF, McGlade C, RemmeU, Wanner B, Varro L, D'Ambrosio D, Spencer T (2021) Net zero by 2050: a roadmap for the global energy sector

Budinis S, Fajardy M, Greenfield C, Moore R (2022) Carbon Capture, utilisation and storage. IEA, Paris

Bustos-Salvagno J (2019) Energy 2050: a participatory process for a long-term energy policy and its role in climate change policies in Chile

Carpenter, Steven M, Long HA (2017) 13—integration of carbon capture in IGCC systems. In: Wang T, Stiegel G (eds) Integrated gasification combined cycle (IGCC) technologies. Woodhead Publishing

Catizzone E, Bonura G, Migliori M, Frusteri F, Giordano G (2017) CO_2 recycling to dimethyl ether: state-of-the-art and perspectives. Molecules 23:31

Chang F-W, Tsay M-T, Liang S-P (2001) Hydrogenation of CO_2 over nickel catalysts supported on rice husk ash prepared by ion exchange. Appl Catal A 209:217–227

Change, IPCC Climate (2013) The physical science basis, Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, 1535: 2013

Cheshideh H, Moslehifard E, Nasirpouri F (2022) 22—TiO_2 nanotube arrays grafted with metals with enhanced electroactivity for electrochemical sensors and devices. In: Hussain CM, Manjunatha JG (eds) Functionalized nanomaterial-based electrochemical sensors. Woodhead Publishing

Commission, European, and Directorate-General for Climate Action (2019) Going climate-neutral by 2050: a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy (Publications Office)

Crippa M, Guizzardi D, Muntean M, Schaaf E, Solazzo E, Monforti-Ferrario F, Olivier JGJ, Vignati E (2020) Fossil CO_2 emissions of all world countries. European Commission, Luxembourg, pp 1–244

Crippa M, Guizzardi D, Banja M, Solazzo E, Muntean M, Schaaf E, Pagani F, Monforti-Ferrario F, Olivier JGJ, Quadrelli R (2022)

CO_2 emissions of all world countries. Publications Office of the European Union, Luxembourg

Cubo E (2010) Hydrocarbons. In: Kompoliti K, Metman LV (eds) Encyclopedia of movement disorders. Academic Press, Oxford

Dahlhoff G, Eickelberg W, Hölderich WF (2001) Recent developments in the catalyst regeneration for the beckmann rearrangement of cyclohexanone oxime to ε-caprolactam. In: Spivey JJ, Roberts GW, Davis BH (eds) Studies in surface science and catalysis. Elsevier

Darmawan A, Aziz M (2022) Chapter 2—process and products of biomass conversion technology. In: Darmawan A, Aziz M (eds) Innovative energy conversion from biomass waste. Elsevier

Desa UN (2019) World population prospects 2019: highlights. United Nations Department for Economic and Social Affairs, New York

Dhyani V, Bhaskar T (2019) Chapter 9—pyrolysis of biomass. In: Pandey A, Larroche C, Dussap CG, Gnansounou E, Khanal SK, Ricke S (eds) Biofuels: alternative feedstocks and conversion processes for the production of liquid and gaseous biofuels, 2nd edn. Academic Press

Diego E, Maria J-M, Pourkashanian M (2017) Process analysis of selective exhaust gas recirculation for CO_2 capture in natural gas combined cycle power plants using amines. J Eng Gas Turbines Power 139:121701

Dokania A, Ould-Chikh S, Ramirez A, Cerrillo JL, Aguilar A, Russkikh A, Alkhalaf A, Hita I, Bavykina A, Shterk G (2021) Designing a multifunctional catalyst for the direct production of gasoline-range isoparaffins from CO_2. JACS Au 1:1961–1974

Dry ME (2002) The Fischer–Tropsch process: 1950–2000. Catal Today 71:227–241

Ebi KL, Balbus JM, Luber G, Bole A, Allison Crimmins G, Glass SS, Shimamoto MM, Trtanj J, White-Newsome JL (2018) Human health impacts, risks, and adaptation in the United States. Fourth Natl Clim Assess 2:539–571

Ebi KL, Vanos J, Baldwin JW, Bell JE, Hondula DM, Errett NA, Hayes K, Reid CE, Saha S, Spector J (2021) Extreme weather and climate change: population health and health system implications. Annu Rev Public Health 42:293–315

Ebnesajjad S (2016) Effect of Chemicals on Plastics. In: Baur E, Ruhrberg K, Woishnis W (eds) Chemical resistance of commodity thermoplastics. William Andrew Publishing

Eldesouki M, Abo-Shanab ZL, El-Shafie M, Abo-Riya M, El-Kholy SA (2022) Fabrication and evaluation of novel sulfur/epoxy resin composites. Polym Bull. https://doi.org/10.1007/s00289-022-04641-0

El-Khatib KM, Abou Helal MO, El-Moneim AA, Tawfik H (2004) Corrosion stability of SUS316L HVOF sprayed coatings as lightweight bipolar plate materials in PEM fuel cells. Anti-Corros Methods Mater 51:136–142

El-Moneim AA, Akiyama E, Ismail KM, Hashimoto K (2011) Corrosion behaviour of sputter-deposited Mg–Zr alloys in a borate buffer solution. Corros Sci 53:2988–2993

Fabry VJ, Seibel BA, Feely RA, Orr JC (2008) Impacts of ocean acidification on marine fauna and ecosystem processes. ICES J Mar Sci 65:414–432

Figuerola B, Hancock AM, Bax N, Cummings VJ, Downey R, Griffiths HJ, Smith J, Stark JS (2021) A review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the Southern Ocean. Front Mar Sci 8:584445

Garba MD, Usman M, Khan S, Shehzad F, Galadima A, Ehsan MF, Ghanem AS, Humayun M (2021) CO_2 towards fuels: a review of catalytic conversion of carbon dioxide to hydrocarbons. J Environ Chem Eng 9:104756

Gazzani M, Macchi E, Manzolini G (2013) CO_2 capture in integrated gasification combined cycle with SEWGS–part A: thermodynamic performances. Fuel 105:206–219

Gielen D, Gorini R, Wagner N, Leme R, Gutierrez L, Prakash G, Asmelash E, Janeiro L, Gallina G, Vale G (2019) Global energy transformation: a roadmap to 2050

González-Castaño M, Dorneanu B, Arellano-García H (2021) The reverse water gas shift reaction: a process systems engineering perspective. React Chem Eng 6:954–976

Guda VK, Steele PH, Penmetsa VK, Li Q (2015) Chapter 7—Fast pyrolysis of biomass: recent advances in fast pyrolysis technology. In: Pandey A, Bhaskar T, Stöcker M, Sukumaran RK (eds) Recent advances in thermo-chemical conversion of biomass. Elsevier, Boston

Guettel R, Turek T (2009) Comparison of different reactor types for low temperature Fischer–Tropsch synthesis: a simulation study. Chem Eng Sci 64:955–964

Guettel R, Kunz U, Turek T (2008) Reactors for Fischer-Tropsch Synthesis. Chem Eng Technol: Ind Chem-Plant Equip-Process Eng-Biotechnol 31:746–754

Gunjal PR, Ranade VV (2016) Chapter 7—catalytic reaction engineering. In: Joshi SS, Ranade VV (eds) Industrial catalytic processes for fine and specialty chemicals. Elsevier, Amsterdam

Hanif MA, Nadeem F, Tariq R, Rashid U (2022) Chapter 3—future energy options: an overview. In: Hanif MA, Nadeem F, Tariq R, Rashid U (eds) Renewable and alternative energy resources. Academic Press

Hannula I, Kaisalo N, Simell P (2020) Preparation of synthesis gas from CO_2 for Fischer–Tropsch Synthesis—comparison of alternative process configurations. C 6:55

Harun R, Singh M, Forde GM, Danquah MK (2010) Bioprocess engineering of microalgae to produce a variety of consumer products. Renew Sustain Energy Rev 14:1037–1047

Hassan MH, Abu FS, Zarren G, Suleiman N, Tahir AA, Snape CE (2020) Kinetic and thermodynamic evaluation of effective combined promoters for CO_2 hydrate formation. J Nat Gas Sci Eng 78:103313

Hastings A, Smith P (2020) Achieving net zero emissions requires the knowledge and skills of the oil and gas industry. Front Clim 2:601778

Hockstad L, Hanel L (2018) Inventory of US greenhouse gas emissions and sinks. In.: Environmental system science data infrastructure for a virtual ecosystem

Hu J, Liang Yu, Deng J, Wang Y, Cheng K, Ma C, Qinghong Zhang Wu, Wen SY, Pan Y (2021) Sulfur vacancy-rich MoS_2 as a catalyst for the hydrogenation of CO_2 to methanol. Nat Catal 4:242–250

IEA (2021) Global energy review: CO_2 emissions in 2021—analysis

Iglina T, Iglin P, Pashchenko D (2022) Industrial CO_2 capture by algae: a review and recent advances. Sustainability 14:3801

Inglezakis VJ, Poulopoulos SG (2006) 3—heterogeneous processes and reactor analysis. In: Inglezakis VJ, Poulopoulos SG (eds) Adsorption, ion exchange and catalysis. Elsevier, Amsterdam

Inumaru J, Hasegawa T, Shirai H, Nishida H, Noda N, Ohyama S (2021) Fossil fuels combustion and environmental issues. In: Ozawa M, Asano H (eds) Advances in power boilers. Elsevier

Irlam L (2017) Global costs of carbon capture and storage, Global CCS institute, 16

Ishaq H, Ali U, Sher F, Anus M, Imran M (2021) Process analysis of improved process modifications for ammonia-based post-combustion CO_2 capture. J Environ Chem Eng 9:104928

Janke C, Duyar MS, Hoskins M, Farrauto R (2014a) Catalytic and adsorption studies for the hydrogenation of CO_2 to methane. Appl Catal B 152–153:184–191

Janke C, Duyar MS, Hoskins M, Farrauto R (2014b) Catalytic and adsorption studies for the hydrogenation of CO_2 to methane. Appl Catal B 152:184–191

Jansen D, Gazzani M, Manzolini G, van Dijk E, Carbo M (2015) Pre-combustion CO2 capture. Int J Greenh Gas Control 40:167–187

Jia X, Sun K, Wang J, Shen C, Liu C-J (2020) Selective hydrogenation of CO_2 to methanol over Ni/In_2O_3 catalyst. J Energy Chem 50:409–415

Jiang H, Lin J, Wu X, Wang W, Chen Y, Zhang M (2020) Efficient hydrogenation of CO_2 to methanol over $Pd/In_2O_3/SBA-15$ catalysts. J CO2 Util 36:33–39

Jurado N, Darabkhani HG, Anthony EJ, Oakey JE (2015) Oxy-fuel combustion for carbon capture and sequestration (CCS) from a coal/biomass power plant: experimental and simulation studies. In: Dincer I, Colpan C, Kizilkan O, Ezan M (eds) Progress in clean energy, vol 2. Springer, Cham

Kaltschmitt T, Deutschmann O (2012) Chapter 1—fuel processing for fuel cells. In: Sundmacher K (ed) Advances in chemical engineering. Academic Press

Kamkeng ADN, Wang M, Jun Hu, Wenli Du, Qian F (2021) Transformation technologies for CO_2 utilisation: current status, challenges and future prospects. Chem Eng J 409:128138

Kawanami H, Himeda Y, Laurenczy G (2017) Chapter ten— formic acid as a hydrogen carrier for fuel cells toward a sustainable energy system. In: van Eldik R, Hubbard CD (eds) Advances in inorganic chemistry. Academic Press

Krishnaiah D, Awang Bono SM, Anisuzzaman CJ, Khee TB (2014) Carbon dioxide removal by adsorption. J Appl Sci 14:3142–3148

Kumar S, Srivastava R, Koh J (2020) Utilization of zeolites as CO_2 capturing agents: advances and future perspectives. J CO2 Util 41:101251

Lei Z, Zou Z, Dai C, Li Q, Chen B (2011) Synthesis of dimethyl ether (DME) by catalytic distillation. Chem Eng Sci 66:3195–3203

Leung JYS, Zhang S, Connell SD (2022) Is ocean acidification really a threat to marine calcifiers? A systematic review and meta-analysis of 980+ studies spanning two decades. Small 18:2107407

Lois E, Keating EL, Gupta AK (2003) Fuels. In: Meyers RA (ed) Encyclopedia of physical science and technology, 3rd edn. Academic Press, New York

Mafwele BJ, Lee JW (2022) Relationships between transmission of malaria in Africa and climate factors. Sci Rep 12:14392

Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI (2021a) Climate change 2021a: the physical science basis, contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change: 2

Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI (2021b) Climate change 2021b: the physical science basis, contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, 2

McCoy ST, Rubin ES (2008) An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. Int J Greenh Gas Control 2:219–229

Mehta P (2010) Science behind acid rain: analysis of its impacts and advantages on life and heritage structures. South Asian J Tour Herit 3:123–132

Meng F, Nawaz MA (2022) Review of slurry bed reactor for carbon one chemistry

Metz B, Ogunlade Davidson HC, Coninck De, Loos M, Meyer L (2005) IPCC special report on carbon dioxide capture and storage. Cambridge University Press, Cambridge

Mills NL, Donaldson K, Hadoke PW, Boon NA, MacNee W, Cassee FR, Sandström T, Blomberg A, Newby DE (2009) Adverse cardiovascular effects of air pollution. Nat Clin Pract Cardiovasc Med 6:36–44

Moret S, Dyson PJ, Laurenczy G (2014) Direct synthesis of formic acid from carbon dioxide by hydrogenation in acidic media. Nat Commun 5:1–7

Nasser AL, Hassan LG, Elnaggar H, Wang Y, Guo X, AbdelMoneim A, Tsubaki N (2018) Mn–Fe nanoparticles on a reduced graphene oxide catalyst for enhanced olefin production from syngas in a slurry reactor. RSC Adv 8:14854–14863

Nelabhotla ABT, Pant D, Dinamarca C (2021) Chapter 8—power-to-gas for methanation. In: Aryal N, Ottosen LDM, Kofoed MVW, Pant D (eds) Emerging technologies and biological systems for biogas upgrading. Academic Press

Ng KL, Chadwick D, Toseland BA (1999) Kinetics and modelling of dimethyl ether synthesis from synthesis gas. Chem Eng Sci 54:3587–3592

Ngarakana-Gwasira ET, Bhunu CP, Masocha M, Mashonjowa E (2016) Assessing the role of climate change in malaria transmission in Africa, Malaria research and treatment, 2016

Obora Y, Ishii Y (2014) 7.09 oxidation of C–H bond adjacent to oxygen of ethers. In: Knochel P (ed) Comprehensive organic synthesis, 2nd edn. Elsevier, Amsterdam

Onyeaka H, Miri T, Obileke K, Hart A, Anumudu C, Al-Sharify ZT (2021) Minimizing carbon footprint via microalgae as a biological capture. Carbon Capture Sci Technol 1:100007

Organization, World Health (2015) Climate and health country profiles 2015: a global overview

Parham PE, Michael E (2010) Modeling the effects of weather and climate change on malaria transmission. Environ Health Perspect 118:620–626

Pegov SA (2008) Methane in the atmosphere. In: Jørgensen SE, Fath BD (eds) Encyclopedia of ecology. Academic Press, Oxford

Perera F (2018) Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: solutions exist. Int J Environ Res Public Health 15:16

Perera F, Ashrafi A, Kinney P, Mills D (2019) Towards a fuller assessment of benefits to children's health of reducing air pollution and mitigating climate change due to fossil fuel combustion. Environ Res 172:55–72

Plan, REPowerEU (2018) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions

Portillo E, Gandara-Loe J, Reina TR, Pastor-Pérez L (2023) Is the RWGS a viable route for CO_2 conversion to added value products? A techno-economic study to understand the optimal RWGS conditions. Sci Total Environ 857:159394

Pörtner H-O (2008) Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. Mar Ecol Prog Ser 373:203–217

Prasad R, Gupta SK, Shabnam N, Oliveira CYB, Nema AK, Ansari FA, Bux F (2021) Role of microalgae in global CO_2 sequestration: physiological mechanism, recent development, challenges, and future prospective. Sustainability 13:13061

Previtali D, Longhi M, Galli F, Di Michele A, Manenti F, Signoretto M, Menegazzo F, Pirola C (2020) Low pressure conversion of CO_2 to methanol over Cu/Zn/Al catalysts The Effect of Mg, Ca and Sr as Basic Promoters. Fuel 274:117804

Priddle R (2002) World energy outlook 2002, International Energy Agency, IEA/OECD, Paris

Qureshi Y, Ali U, Sher F (2021) Part load operation of natural gas fired power plant with CO_2 capture system for selective exhaust gas recirculation. Appl Therm Eng 190:116808

Rahimpour MR, Dehnavi MR, Allahgholipour F, Iranshahi D, Jokar SM (2012) Assessment and comparison of different catalytic coupling exothermic and endothermic reactions: a review. Appl Energy 99:496–512

Rajmohan KS, Yadav H, Vaishnavi S, Gopinath M, Varjani S (2020) Chapter 23—perspectives on bio-oil recovery from plastic waste. In: Varjani S, Pandey A, Gnansounou E, Khanal SK,

Raveendran S (eds) Current developments in biotechnology and bioengineering. Elsevier

Rashed AE, Essam K, El Kady MF, Yoshihisa M, El-Moneim AA, AL-Hassan Mohammed Nasser. (2021) Highly active fischer-tropsch synthesis Fe-BDC MOF-derived catalyst prepared by modified solvothermal method. Key Eng Mater 891:56–61

Rashed AE, Nasser A, Elkady MF, Matsushita Y, El-Moneim AA (2022) Fe Nanoparticle Size Control of the Fe-MOF-derived catalyst using a solvothermal method: effect on FTS activity and olefin production. ACS Omega 7:8403–8419

Rashed AE, Nasser A, Elkady MF, Matsushita Y, El-Moneim AA (2023) Temperature calibration effect on FTS activity and product selectivity using Fe-MOF catalyst. Case Stud Chem Environ Eng 7:100300

Rauch R, Kiennemann A, Sauciuc A (2013) Chapter 12—Fischer–Tropsch synthesis to biofuels (BtL process). In: Triantafyllidis KS, Lappas AA, Stöcker M (eds) The role of catalysis for the sustainable production of bio-fuels and bio-chemicals. Elsevier, Amsterdam

Reay D, Ramshaw C, Harvey A (2013) Chapter 5—reactors. In: Reay D, Ramshaw C, Harvey A (eds) Process intensification, 2nd edn. Butterworth-Heinemann, Oxford

Ritchie H, Roser M, Rosado P (2020) CO_2 and greenhouse gas emissions, Our world in data

Robles H (2005) Formic acid. In: Wexler P (ed) Encyclopedia of toxicology, 2nd edn. Elsevier, New York

Rojas-Andrade MD, Chen S (2018) Structural engineering of nanoparticle catalysts for electrochemical oxidation of formic acid. In: Wandelt K (ed) Encyclopedia of interfacial chemistry. Elsevier, Oxford

Rubin ES, Rao AB, Chen C (2005) Comparative assessments of fossil fuel power plants with CO_2 capture and storage. In: Greenhouse gas control technologies 7, Elsevier

Ryan C, Hartley A, Browning B, Garvin C, Greene N, Steger C (2009) Cultivating clean energy, The promise of algae biofuels. Springer, Singapore, 1–65

Saeidi S, Amiri MT, Amin NAS, Rahimpour MR (2014) Progress in reactors for high-temperature Fischer–Tropsch process: determination place of intensifier reactor perspective. Int J Chem Reactor Eng 12:639–664

Sastre F, Puga AV, Liu L, Corma A, Garcia H (2014) Complete photocatalytic reduction of CO_2 to methane by H_2 under solar light irradiation. J Am Chem Soc 136:6798–6801

Schorn F, Breuer JL, Samsun RC, Schnorbus T, Heuser B, Peters R, Stolten D (2021) Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations. Adv Appl Energy 3:100050

Schubert PF, Bayens CA, Weick L, Haid MO (2001) Expanding markets for GTL fuels and specialty products. In: Iglesia E, Spivey JJ, Fleisch TH (eds) Studies in surface science and catalysis. Elsevier

Scranton MI, de Angelis MA (2001) Gas exchange in estuaries. In: Steele JH (ed) Encyclopedia of ocean sciences, 2nd edn. Academic Press, Oxford

Senatore A, Lania I, Corrente GA, Basile A (2020) Chapter 18—CO_2 capture by bacteria and their enzymes. In: Rahimpour MR, Farsi M, Makarem MA (eds) Advances in carbon capture. Woodhead Publishing

Shee S, Paul B, Kundu S (2022) Chapter 3—transition metal-catalyzed dehydrogenation of methanol and related transformations. In: Kumar A (ed) Pincer-metal complexes. Elsevier

Shen C, Sun K, Zhang Z, Rui N, Jia X, Mei D, Liu C-J (2021) Highly active Ir/In$_2$O$_3$ catalysts for selective hydrogenation of CO_2 to methanol: experimental and theoretical studies. ACS Catal 11:4036–4046

Sher F, Chen S, Raza A, Rasheed T, Razmkhah O, Rashid T, Rafi-ul-Shan PM, Erten B (2021a) Novel strategies to reduce engine emissions and improve energy efficiency in hybrid vehicles. Clean Eng Technol 2:100074

Sher F, Raore D, Klemeš JJ, Rafi-ul-Shan PM, Khzouz M, Marintseva K, Razmkhah O (2021b) Unprecedented impacts of aviation emissions on global environmental and climate change scenario. Current Pollut Rep 7:549–564

Shikada T, Miyoshi Y, Mogi Y, Inoue N, Ohno Y (2007) 23—new direct synthesis technology of dimethyl ether. In: Eguchi K, Machida M, Yamanaka I (eds) Studies in surface science and catalysis. Elsevier

Singh A, Agrawal M (2007) Acid rain and its ecological consequences. J Environ Biol 29:15

Smit B, Park AHA, Gadikota G (2014) The grand challenges in carbon capture, utilization, and storage. Front Energy Res. https://doi.org/10.3389/fenrg.2014.00055

Solaymani S (2019) CO_2 emissions patterns in 7 top carbon emitter economies: the case of transport sector. Energy 168:989–1001

Song H, Yang J, Zhao J, Chou L (2010) Methanation of carbon dioxide over a highly dispersed Ni/La$_2$O$_3$ Catalyst. Chin J Catal 31:21–23

Stauffer E, Dolan JA, Newman R (2008) Chapter 7—flammable and combustible liquids. In: Stauffer E, Dolan JA, Newman R (eds) Fire debris analysis. Academic Press, Burlington

Stewart M, Arnold K (2011) Part 1 - gas sweetening 1, 2. In: Stewart M, Arnold K (eds) Gas sweetening and processing field manual. Gulf Professional Publishing, Boston

Suleiman Y, Ibrahim H, Anyakora NV, Mohammed F, Abubakar A, Aderemi BO, Okonkwo PC (2013) Design and fabrication of fluidized-bed reactor. Int J Eng Comput Sci 2:1595–1605

Suppes GJ, Storvick TS (2016) Chapter 3—energy and sustainability. In: Suppes GJ, Storvick TS (eds) Sustainable power technologies and infrastructure. Academic Press, Boston

Svensson R, Odenberger M, Johnsson F, Strömberg L (2004) Transportation systems for CO_2—application to carbon capture and storage. Energy Convers Manag 45:2343–2353

Ting KW, Takashi Toyao SMA, Siddiki H, Shimizu K-I (2019) Low-temperature hydrogenation of CO_2 to methanol over heterogeneous TiO$_2$-Supported Re catalysts. ACS Catal 9:3685–3693

Vale MA, Ferreira A, Pires JCM, Gonçalves AL (2020) Chapter 17—CO_2 capture using microalgae. In: Rahimpour MR, Farsi M, Makarem MA (eds) Advances in carbon capture. Woodhead Publishing

Vega F, Cano M, Camino S, Gallego Fernández LM, Portillo E, Navarrete B (2018) Solvents for carbon dioxide capture, Carbon dioxide chemistry, capture and oil recovery: 142–163

Verhelst S, Turner JWG, Sileghem L, Vancoillie J (2019) Methanol as a fuel for internal combustion engines. Prog Energy Combust Sci 70:43–88

Wang X, Economides M (2009) Chapter 7—gas-to-liquids (GTL). In: Wang X, Economides M (eds) Advanced natural gas engineering. Gulf Publishing Company

Wang S, Li X, Hong Wu, Tian Z, Xin Q, He G, Peng D, Chen S, Yin Y, Jiang Z (2016) Advances in high permeability polymer-based membrane materials for CO_2 separations. Energy Environ Sci 9:1863–1890

Wang Y, Zhao Li, Otto A, Robinius M, Stolten D (2017) A review of post-combustion CO_2 capture technologies from coal-fired power plants. Energy Procedia 114:650–665

Wei J, Ge Q, Yao R, Wen Z, Fang C, Guo L, Hengyong Xu, Sun J (2017) Directly converting CO_2 into a gasoline fuel. Nat Commun 8:15174

Worstell J (2014) Chapter 3—catalyst deactivation. In: Worstell J (ed) Adiabatic fixed-bed reactors. Butterworth-Heinemann, Boston

Wu Z (2019) Chapter 5—inorganic membranes for gas separations. In: Ismail AF, Rahman MA, Othman MHD, Matsuura T (eds) Membrane separation principles and applications. Elsevier

Xie L, Xu J, Zhang Y, He Y (2020) Chapter seven—biogas upgrading. In: Li Y, Khanal SK (eds) Advances in bioenergy. Elsevier

Xiong S, Lian Y, Xie H, Liu B (2019) Hydrogenation of CO_2 to methanol over Cu/ZnCr catalyst. Fuel 256:115975

Xu X, Wang J, Zhou A, Dong S, Shi K, Li B, Han J, O'Hare D (2021) High-efficiency CO_2 separation using hybrid LDH-polymer membranes. Nat Commun 12:1–10

Yang H, Zhenghe Xu, Fan M, Gupta R, Slimane RB, Bland AE, Wright I (2008) Progress in carbon dioxide separation and capture: a review. J Environ Sci 20:14–27

Yeh JT, Resnik KP, Rygle K, Pennline HW (2005) Semi-batch absorption and regeneration studies for CO_2 capture by aqueous ammonia. Fuel Process Technol 86:1533–1546

Yin C, Qiu S, Zhang S, Sher F, Zhang H, Jian Xu, Wen L (2020) Strength degradation mechanism of iron coke prepared by mixed coal and Fe_2O_3. J Anal Appl Pyrol 150:104897

Zhang M, Guo Y (2013) Rate based modeling of absorption and regeneration for CO_2 capture by aqueous ammonia solution. Appl Energy 111:142–152

Zhang M, Guo Y (2017) Analysis on regeneration energy of NH_3-based CO_2 capture with equilibrium-based simulation method. Energy Procedia 114:1480–1487

Zhang Y, Ran Z, Jin B, Zhang Y, Zhou C, Sher F (2019) Simulation of particle mixing and separation in multi-component fluidized bed using Eulerian-Eulerian method: a review. Int J Chem Reactor Eng 17:20190064

Zhang Z, Zeng Y, Zheng N, Luo Li, Xiao H, Xiao H (2020) Fossil fuel-related emissions were the major source of NH_3 pollution in urban cities of northern China in the autumn of 2017. Environ Pollut 256:113428

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